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5 Pollux Drive
Edwards AFB CA 93524-7048

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The USAF Electric Propulsion Program

R. A. Spores
Propulsion Directorate
Air Force Research Laboratory
Edwards AFB, CA

M. Birkan
Air Force Research Laboratory/AFOSR
Bolling AFB, Washington, DC

# 34th AIAA/ASME/SAE/ASEE
# Joint Propulsion Conference & Exhibit
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# The USAF Electric Propulsion Program

Ronald A. Spores*, Air Force Research Laboratory/Propulsion Directorate, Edwards AFB, CA 93524
Mitat Birkan*, Air Force Research Laboratory/ AFOSR, Bolling AFB, Washington, DC 20332

## Abstract

An overview of the current state of electric propulsion technology development efforts within the United States Air Force is presented. Air Force Mission Needs Statements which call for electric propulsion are likewise discussed. Two groups within the Air Force Research Laboratory contribute to the electric propulsion program: Propulsion Directorate and Air Force Office of Scientific Research (AFOSR). The Propulsion Directorate is conducting electric propulsion efforts in basic research, engineering development, as well as an Advanced Technology Development effort that will result in a space flight experiment of a 30 kilowatt arcjet system. AFOSR funds basic research in electric propulsion throughout the country in both academia and industry.

## I. Introduction

The requirement of higher satellite performance at lower cost has been a driving force towards electric propulsion, with the commercial sector so far leading the way. Within the Air Force (AF) there has been a reluctance to implement more advanced on-orbit propulsion technologies because of real and perceived risks; this is changing. MightySat, Clementine, ISTF, MSTI, and STEP are examples of AF space experiment programs with the goal of demonstrating advanced technologies for future DoD satellites. MILSATCOM has baselined electrostatic propulsion for its post-2000 satellites, and Air Force SMC is flying the ESEX spacecraft to demonstrate a 26-kW ammonia arcjet on orbit. Military satellites which could benefit from electric propulsion include: MILSATCOM, DSP, DSCS, SBIRS, a proposed Space Based Radar constellation, and a proposed orbit transfer vehicle.

Over the last several years the Air Force interest in electric propulsion was primarily directed at the north-south stationkeeping of DSCS follow-on (Advanced MILSATCOM). Chemical propulsion was baselined for all transfers to operational orbits. With the rise in available bus power in recent years, rapid progress toward maturation of high power electric thruster technology, and tolerable transfer times for combined electric-chemical orbit transfer, the use of electric technology for orbit transfer is being considered for

some programs in view of the demonstrated value from a missions analysis standpoint.

## Air Force Planning Process

U.S. Space Command and the Air Force recognize that electric propulsion will be a key technology in the area of launch and spacecraft operations for future military spacecraft. This recognition is stated in the Air Force Space Command's Strategic Master Plan and its supporting documents: Science and Technology Mission Support Plan(MSP)[1] and the Launch Operations Sub-Mission Area Development Plan (LO-SMADP). Electric propulsion could be an enabling factor in the areas of space force enhancement (support to the warfighter), space control (total control of the space environment), and space force application (weapons in/from space).

The Mission Support Plan ensures continuous, focused science and technology investment by the Air Force Research Laboratory (AFRL) in the areas most likely to bring about the transition from today's Air Force to, ultimately, a Space and Air Force. The MSP takes into account the new scientific era where DoD is no longer the clear leader in R & D of cutting-edge technologies, while civilian, academic, and industry sectors are increasingly focused on commercial applications. The plan encompasses long-range planning documents like: U.S. Space Command Vision for 2020, the Joint Warfighting Science and Technology Plan (JWSTP) and the New World Vista study. LO-SMADP is the primary source of launch and upperstage operations information and includes an overview of the current launch operations architecture, potential future architectures, and the technology investment needed to develop the included concepts. Electric propulsion has become a very important part of the MADP beginning with the 1995 edition, and electric orbit transfer is included in some detail in the 1998 document.

LO-SMADP specifically mentions areas for development in electric propulsion. Technology development of both high and low power arcjet thrusters, pulsed plasma thrusters (PPTs), plasma thrusters (both SPTs and TALs), and gridded ion engines is needed to support the full range of forthcoming government missions. Efforts to characterize these thrusters are required to further understand their performance potential, failure mechanisms, life limiting factors, and integration impacts. Issues for arcjet applications include cathode life extension and anode erosion resistance. Low

be explored. SPTs and TALs still need work on efficiency, materials erosion characterization, and beam divergence issues. Cathode improvement is critical for SPTs, TALs, and ion engines, especially as low power engines are developed for forthcoming small satellites. Development of gridded ion engines should focus on grid and discharge chamber erosion rates, contamination fluid on spacecraft surfaces, and segmented or annular grid designs for high power operation. All thruster systems would benefit from reductions in weight, cost, and parts count of the power processing unit and from development of lightweight, radiation hardened, higher performance solar arrays.

## FUTURE AIR FORCE MISSIONS
25 years from now, the Air Force will still have the need to launch manifested satellites and the desire to do so at a much reduced cost. In addition, visionary documents see future launch operations expanding to include wartime rapid response launch, in-space wartime operations, on-orbit servicing, and satellite recovery. Investing in structures, propulsion, operability technology, and more will allow the Air Force to achieve its visions of the future. The Air Force has identified a list of deficiencies in the current space operations architecture: 1) Costly Spacelift (where Spacelift is defined as launch and upperstage), 2) Unresponsive Spacelift, 3) Satellite Recovery and On-Orbit Service, 4) Satellite Repositioning, 5) Global Mobility Via Space. How electric propulsion can help these deficiencies will be discussed.

### Advanced Upper Stage for Space lift
Advanced Upper Stages are improved expendable and integral upper stages that utilize higher Isp solar electric propulsion, solar thermal propulsion, and advanced chemical propulsion systems. Utilizing improved upperstages for orbit transfer and high Isp electric thrusters for apogee kick motors and stationkeeping, allows for greatly increased mission payload. Higher Isp systems reduce the amount of propellant needed for orbit transfer and/or on-orbit maintenance, and thus, they help make the overall upper stage/OTV and satellite smaller, lighter and cheaper. Furthermore, current chemical satellite propulsion systems do not meet the need for maneuverability and life. They are limited in the number of repositioning moves they can make and still maintain an adequate life on orbit.

The Strategic Master Plan states: Military Space Plane, along with Expendable Launch Vehicles, require a suite of efficient upper stages for insertion into final operational orbits. High specific impulse with modest thrust is desired to reduce transfer times while maintaining very favorable payload mass fractions. Incorporation of (electric propulsion) into future space

tugs to provide cost-effective orbit insertion and potential retrieval is a future opportunity.

The FY98 LO-SMADP discusses various electric propulsion options relevant to upper stage capabilities, which are a major driver for launch vehicle performance requirements and the overall cost of spacelift. Three upper stage classes having different cost and performance trade-offs are discussed in some detail in the MADP: expendable, integral, and reusable. An integral upper stage brings a satellite to its operational orbit and then remains with the satellite using the power and propulsion subsystems of the OTV for payload operations and orbital maneuvering. Most geosynchronous communications satellites today utilize an integral chemical upper stage which allows them to circularize at GEO and then provides stationkeeping. Advanced integral upper stages will use electric propulsion systems. An expendable upper stage is a traditional orbit transfer vehicle containing propulsion, power, and GN&C systems that are used for reaching operational orbit. Upon reaching mission orbit, the expendable upper stage separates from the satellite and becomes space debris. integral propulsion systems offer longer satellite lifetimes over expendable. The reusable upper stage is an independent space tug with the capability to lift a satellite to its final orbit, and return to low earth orbit for another mission. A reusable upper stage enables recovery, repositioning, deorbiting, rendezvous and docking, space debris removal, survivability movement, formation flying, spoofing, slot denial, and incapacitation/kinetic kill. The development of advanced upper stages is critical for future Air Force missions.

### Satellite Recovery and On-Orbit Service
Satellite recovery and on-orbit service is costly and currently limited to using the space shuttle. Shuttle recovery and repair missions require long planning lead times and are limited to systems in low-altitude, low-inclination (<57 deg) orbits – for example the two Hubble Space Telescope repair missions. The $\Delta V$ requirements for large orbit and/or plane changes can limit the satellite repositioning often needed to accomplish a rendezvous for service or recovery.

Another major effort initiated within the Air Force Research Lab is a program to look into on-orbit servicing of satellites. This program encompasses on-orbit satellite maintenance, repair, and re-supply similar in approach to that presently in use on a daily basis with aircraft. This program is an effort to change the philosophy of how satellites are deployed, in order to move away from the present approach where satellites are designed with extensive redundancy, used until failure, and then discarded. The new method would

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provide "Aircraft-Like" inspection, maintenance, and upgrade of space assets and would be incorporated into the space architecture in phases. Near term missions would consist of inspection of space assets. Follow-on applications would incorporate the resupply of expendables onto the satellite and/or the addition of hardware to the satellite at preplanned open ports on the existing spacecraft's bus. Far term missions would be the most ambitious involving satellite decontamination - cleaning of critical devices onboard the vehicle (i.e.- optics) and ultimately repair of the satellite. On-orbit assembly is a long term goal where large satellites would be constructed in space via the autonomous assembly of smaller modules.

The missions being considered for on-orbit servicing would utilize a reusable space vehicle with high $\Delta V$ requirements. Electric propulsion is a natural match for these types of missions. High power, moderate Isp (~1700sec) propulsion is the most likely approach for the reusable space tug. Inspection satellites that would only be used around the mission target will probably be nano/microsats requiring the development of micro-propulsion technology.

### Satellite Repositioning
The ability to reposition on-orbit assets is currently limited to the use of spacecraft attitude control and station-keeping engines. Unanticipated maneuvers greatly decrease satellite life-time. The lack of adequate planning capability and physical capability to store expendable fuel supplies restricts timely satellite repositioning. Maneuver generation and execution takes days versus hours.

Extraordinary repositioning includes large orbit or plane changes that one might want to accomplish to modify the coverage of a satellite. In a wartime situation, one may desire to move a satellite to a more optimal location for the conflict. If the conflict takes place in an area lacking coverage or if satellites covering the area have been incapacitated, one can launch a new satellite or move a satellite already in orbit. Present Air Force opinion is that less than 10 satellite movements will be needed per year with the time to relocate satellites on the order of days. The anticipated $\Delta V$ requirements are <100 m/sec for only altitude change and km/sec for plane change maneuvers.

### Future Air Force Spacecraft
It is likely that several next generation Air Force spacecraft will greatly benefit from high performance electric thrusters for delivery to orbit and routine on-orbit operations. The alternative may be to sacrifice critical satellite capability. EP is not presently in operational use for orbit raising and this role is more demanding than on-orbit stationkeeping and repositioning. MILSATCOM's Advanced EHF and SHF/Ka follow-on are examples of satellites which are expected to benefit from electric orbit transfer and stationkeeping. Space-Based Radar and Space-Based Laser are other candidates for electric propulsion. Electric thrusters are also attractive for a variety of other missions, including drag makeup for low-flying polar orbit spacecraft, microsatellite positioning and maintenance, etc.

### Space Based Radar (SBR)
The use of a large phased array SBR has been proposed for surveillance for multimission defense, air traffic control, and disarmament functions. Certain advantages exist over traditional ground-based systems, including continuous large-scale observation, multiple mission capability, tunable propagation characteristics based on frequency selection, and political independence from foreign countries for station operation.[2] The concepts being considered for SBR cover a huge range of sizes: satellite mass from 70-18000 kg; power range from 1-100 kW; altitude, 700km-GEO; and number of satellites from 3 to 1200.

The SBR is also an attractive application for constellations of microsatellites. SBR is intended to surpass AWAC or JSTAR capability by scanning a 1000 km$^2$ area in 1 minute with 10 m resolution for stationary or fast-moving targets. In order to succeed the critical technical challenge is achieving a sufficiently large imaging aperture. From the high-altitude of space, the required antenna diameter increases to 3.6 km (at a 1000 km LEO orbit). For one SBR concept, the 3.6-km antenna can potentially be achieved with a Phased Array of 120 microsatellite transceivers formation flying in a constellation. Each MicroSat transceiver requires a 2.5 m diameter antenna and has a satellite mass of approximately 20 kg. The SBR propulsion requirements for this microsat concept are: forming ($\Delta V$=2 m/s), Maintaining ($\Delta V$=40 m/s/yr), and attitude control ($\Delta V$=4 m/s/yr). The propulsion requirements for each satellite concept being considered are critical for determining which electric propulsion concepts will be pursued by the Air Force in the future.

Two key technologies that could lead to the successful deployment of a large phased array SBR propulsion and power. Advanced propulsion systems are required for orbit transfer and station keeping in order to maximize payload delivered and minimize launch costs. High power systems are required for radar operation. Electric propulsion systems appear attractive because the high power system required for electric propulsion may be used to power SBR after its initial duty for orbit transfer.

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## Space Based Laser

The Space-Based Laser Readiness Demonstrator, (SBLRD) is intended to demonstrate the technical feasibility of a space-based laser system to intercept and destroy theater ballistic missiles in their boost phase. Laser-based missile defense systems offer several advantages over traditional missile defense systems: faster operation, less expense, and ability to react within hours of a surprise attack.

Each team will incorporate into its SBLRD concept the four main elements associated with space-based laser design – a hydrogen fluoride laser, a reactant feed and storage system, a beam director for acquisition, tracking and pointing, and the satellite itself, which will house the three payloads. Future concepts for a space based laser system as well as some classified payloads require lift capabilities greater than our current systems can accommodate ($\geq 50,000$ lbs to LEO). Electric propulsion might be beneficial for reducing the size of these proposed systems.

## Space Based Infrared System (SBIRS)

SBIRS will replace the Defense Support Program (DSP) as the U.S.'s primary initial warning system of a ballistic missile attack on the U.S., its deployed forces, or it allies. It will provide improved battlespace situational awareness and intelligence support. The SBIRS High and Low components (with highly elliptical and geosynchronous orbiting satellites, and low earth orbiting satellites, respectively) will provide global below- and above-the-horizon missile detection, tracking, and discrimination in their boost, post-boost, midcourse and reentry phases of flight. An integrated, centralized ground station will serve all SBIRS space elements (as well as DSP satellites). SBIRS will provide advanced surveillance and warning capability needed to support both theater and national ballistic missile defenses (BMD), as well as intelligence community needs, into the 21st century.

## Micropropulsion

There is presently a strong interest in the development of microsatellites within the Air Force and DARPA.

This strong interest is best typified by the Micro/Nanotechnology for Micro/Nanosatellites Workshop sponsored by the Air Force Research Laboratory on 21-22 April 1998.[3] The definition of a microsatellite that was recommended by this workshop is a mass of 10-100 kg with a nanosatellite in the mass range of 1-10 kg. There are presently three programs that AFRL is working in the area of electric micropropulsion: 1) micro pulsed plasma thruster, 2) Small/ micro Hall thrusters in the 100 W class size range, and 3) the free molecular resistojet. Each of these options is appropriate for a different size MicroSat and different mission. All three of these concepts are in various stages of the patent process.

MicroPropulsion is still in its infancy. Further development of current concepts is needed and new innovative concepts must also be pursued. The top US laboratories are presently pursuing a wide range of schemes. The fast-paced development of these propulsion units will accelerate in the next few years, although most of the system requirements for microsatellite missions must be better defined to determine the best propulsion concepts. For micropropulsion systems, the ever important factors of overall volume and dry mass become even more critical. Solid propellants look attractive on this small scale because they eliminate valves and tanks. The classic rocket equation dictates that high Isp is still very desireable if the mission has a substantial $\Delta V$. Variable thrust from a single propulsion system is advantageous to accomplish everything from orbit insertion to ACS. Once simple engineering and low power requirements are included in the trade space, the result is a monumental design problem.

It is interesting to note that most microthrusters under development are forms of electric propulsion. For large thrusters, we use electric acceleration to achieve high Isp and save propellant mass. In electrical microthrusters, one uses electrical energy storage and pulsed current delivery since it enables the thruster to deliver precise impulse bits of thrust. This is an essential feature for the precision control required for formation flying and Space Command missions. For several Air Force technology investment opportunities, microsatellites enable or greatly enhance the missions. These opportunities are: 1) Some concepts of SBR 2) Space Control, a close-up inspection of other satellites, and 3) On-Orbit Maintenance, Assembly and Resupply (MAR).

## Self-Consuming Satellites

The traditional approach in designing satellites is to structurally stiffen the satellite so that it will survive

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during the launch environments; once on-orbit, a substantial portion of the satellite structural mass is no longer needed. This approach is very inefficient, considering that a kg of mass costs tens of thousands of dollars to put into space. Therefore, the Air Force is interested in devising methods to structurally stiffen the satellite so that the stiffening elements can be used for other purposes. One such concept is to have the satellite propellant a part of the satellite's load bearing structure. This will lead to: lighter satellites, decreased spacecraft volume, and gradual increases in payoff as the spacecraft structure mass decreases for each pulse generated.

The goal of this effort is to utilize current state of the art micropropulsion systems, and determine unique ways to have the propellant a part of the load bearing structure. One possible propulsion technique that may be useful in a self-consuming satellite is a pulsed plasma thruster that uses Teflon™ as the propellant. Teflon™, since it is a solid, has the potential of being a stiffening element of the satellite structure. For example, Teflon™ tubes may be used as longitudinal stiffeners for the sides of the satellite bus. Another possible propulsion system for self-consuming satellite is the digital microthruster being developed by TRW under a DARPA contract. This system is a series of several hundred thousand microthrusters that have the propellant sealed in a container by burst disks. To use any individual microthruster, a heating element is activated causing the pressure inside to build until the burst disk ruptures causing a thrust impulse. This system has the potential of replacing, or at least lessening the wall thickness of the satellite bus; thereby reducing weight. Part of the analysis for any concept will include investigation of how the structural bus' natural frequency will be directly affected by changes in its stiffness and mass properties throughout the propellant consumption.

## II. Space Experiments

### MightySat II.1 Demo of a H₂O Resistojet
The first use of a Mark-IV water resistojet[4] in an orbit raising application for small satellites will be demonstrated in a cooperative effort between AFRL Propulsion Directorate and Space Systems Technology Limited (SSTL) of Surrey, England on the MightySat II.1 satellite. The MightySat program is managed from the Space Vehicles Directorate of AFRL at Kirtland Air Force Base (AFB). Spectrum Astro, of Gilbert, AZ, successfully completed a Detailed Design Review in February and is currently building the first in a series of MightySat II spacecraft. MightySat II.1,

known as Sindri, is scheduled for launch in January, 2000.

The Mk-IV was designed to perform a critical orbit raising maneuver to extend the MightySat II.1 mission life from 50 days to 1 year when released from the Space Shuttle payload bay at an altitude of 220 nautical miles (nm). The January, 2000 launch date places the orbit raising maneuver right at the beginning of the solar maximum cycle, which will dramatically increase spacecraft orbit decay rates. This in turn will increased the demands on the Mk-IV design.

For the MightySat II.1 flight, three Mk-IV thrusters will be constructed. Two will be shipped from Surrey, UK to Edwards AFB, CA and are designated US-1 and US-2. US-1 will undergo a series of performance baseline tests on a thrust stand and then a 300 hour continuous operation test to demonstrate that the Mk-IV can meet the lifetime requirements for the orbit raising mission. After US-2 is received at Edwards, it will go through a brief acceptance performance test and then be shipped to the Aerospace Engineering Facility (AEF) at Kirtland AFB for proto-qual testing. Once the environmental tests on US-2 are complete, the resistojet will be integrated with the MightySat II.1 spacecraft. The third thruster, designated UK-1, will undergo similar performance testing in England concurrent with the US-1 and -2 tests. Additionally, however, UK-1 will be cut open after vibration and life tests to examine the condition of the SiC particle bed.

In addition to the US-2 thruster, a sister payload termed the Plume Diagnostic Experiment (PDE)[5] will determine the effects of plume contamination from the thruster on typical optical surfaces. The PDE consists of two panels on different spacecraft surfaces. Each panel is thermally isolated from the spacecraft and has a quartz crystal microbalance and calorimeter mounted in an insulated enclosure.

### ESEX
The Electric Propulsion Space Experiment (ESEX) is a space demonstration of a 30 kW class ammonia arcjet subsystem. This will set the standard for continuous high power generation in space for an electric propulsion device. ESEX is one of nine experiments scheduled for launch in Dec 98 on the Advanced Research and Global Observation Satellite (ARGOS). ARGOS will be launched on a Delta II into a 460 nautical mile orbit, at 98.7° inclination. The ESEX flight unit completed a flight qualification program and was delivered to the ARGOS prime contractor, Boeing, in early Mar 96. In July, 1998 the integration testing was completed

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with the ARGOS host spacecraft for system-level verification including EMC, acoustic and pyro-shock, and thermal vacuum.

The final spacecraft thermal vacuum testing was recently completed and verified that all spacecraft and experiment systems operate nominally. This integrated space vehicle testing served to verify one of the major objectives for the ESEX program - to demonstrate the feasibility of integrating high power electric propulsion systems with operational satellites. ESEX will measure and record an extensive range of flight data for subsequent comparison to ground results. Operations of the space experiment and subsequent analysis of the data will be conducted jointly by both AFRL and Aerospace Corporation personnel. The flight diagnostic suite includes: four thermoelectrically-cooled quartz crystal microbalance (TQCM) sensors to measure contamination due to arcjet operation, four radiometers to measure radiated heat flux, near- and far-field electromagnetic interference (EMI) antennas, a section of eight gallium-arsenide solar cells to verify no degradation from arcjet operation, a video camera to image the plume, and an accelerometer. In addition, a detailed analysis of the host spacecraft's raw GPS data will be performed, with the objective of providing a time history of thruster performance during firings. Optical signature measurements from observations made with AFRL telescopes on Maui will yield information about ionization and other loss mechanisms in the thruster.
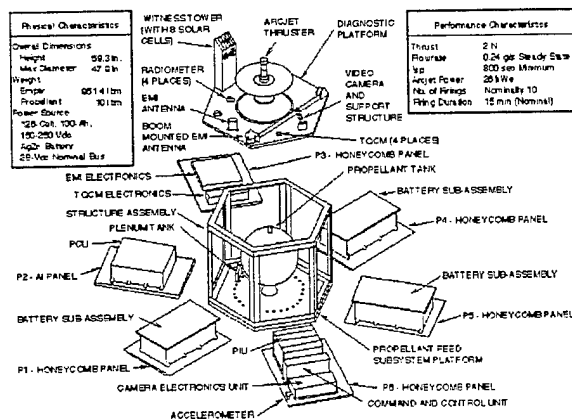


**Figure 1: ESEX Exploded View**

The ESEX flight system, see figure 1, includes a propellant feed system, power subsystem - including a power conditioning unit (PCU) and silver-zinc (Ag-Zn) batteries, commanding and telemetry modules, on-board diagnostics, and the arcjet assembly. ESEX is a self- contained, hexagonal structure which is thermally

isolated from ARGOS. This design philosophy allows ESEX to function autonomously, requiring support only for attitude control, communications, radiation-hardened data storage, and 28 Vdc power for housekeeping functions such as battery charging and thermal control.

**ESEX Optical Signature Measurements**

The primary goal of the ESEX in-flight optical signature measurements is to determine the excitation states, radiance, and extent of the exhaust plume in a free-space expansion. At lower power levels (1.5 kW) in the laboratory, these properties are observed to have dramatically different extent and structure depending on the background pressures. For the 26 kW ESEX power level, laboratory investigations unperturbed by chamber effects are impractical. The ESEX flight offers the first opportunity to observe the plume physics and chemistry of a high-power plasma thruster in a free-space expansion. An intense NH emission, expected in the UV near 336 nm, is considered to be a significant frozen-flow loss since the transition energy is comparable to the particle kinetic energy (~8 to 10 eV). A principal diagnostics used in the optical study is ground-based observations of the plume spectrum using the 1.6 m telescope at the AF Maui Space Surveillance Site (MSSS).
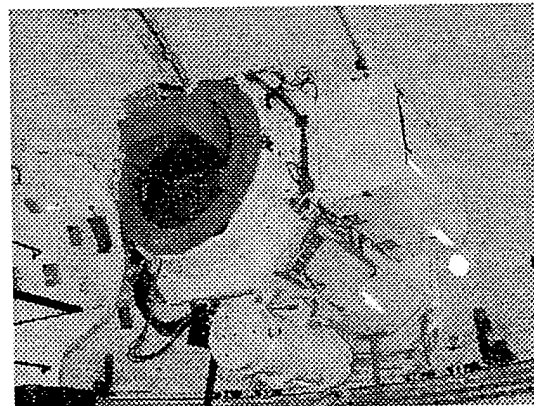


Fig. 2 ESEX Optical Diagnostic package mounted on the rear Blanchard of the MSSS 1.6-m telescope.

The ESEX/MSSS diagnostic package, shown in Fig. 2, is installed on the rear Blanchard of the 1.6 m telescope. When tracking a satellite, the light that does not enter the spectrometer entrance slit is reflected and re-imaged into an intensified CCD camera (Burle ICCD). This provides the telescope operator with an image of the ESEX plume superimposed on the entrance slit - thus enabling tracking of the ARGOS satellite during a firing. Initial tests of the ESEX package determined the minimum light intensity that could be resolved by tracking known stars of

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successively diminishing intensity. Stars were tracked down to 14th visible magnitude, five orders of magnitude below the expected intensity of the ESEX arcjet plume. Calibration of the system is performed using both internal and astrophysical light sources. Externally, large Messier objects (primarily Nebula) are used as emission sources to investigate possible atmospheric effects on the line shape observed at the spectrometer. The most critical calibration for the ESEX tests is to determine the atmospheric UV extinction.

At present, the ESEX optical diagnostic package has been integrated with the MSSS 1.6-m telescope. The diagnostic has been aligned, calibrated, and tested. The capability of the diagnostic package exceeds original design goals and estimates in terms of sensitivity. The ability to track and obtain spectra from a moving satellite has been demonstrated. Presently the diagnostic package remains installed on the telescope Blanchard waiting for the ARGOS launch.

## III. Hall Thruster Programs

### High Performance Hall Thruster System

AFRL is also supporting the development and ground demonstration of a 4.5 kW class Hall thruster propulsion system, the SPT-140, under the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. Flight derivatives of this system will be applicable to orbit raising, station-keeping, and maneuvering applications. The High Performance Hall System (HPHS) program, a four-year effort begun in September 1997, is projected to meet the Phase I IHPRPT spacecraft goal of improving total impulse over wet mass by 20%. The contractor team is led by Atlantic Research Corporation and includes International Space Technology Incorporated, Space Systems/Loral (SS/Loral), Engineering Design Bureau/Fakel (EDB/Fakel), and the Russian Institute of Applied Mechanics and Electrodynamics (RIAME).

The HPHS demonstration effort includes the development and qualification of a flight-like Hall Effect Thruster (HET) and Power Processing Unit (PPU), the integration of flow system and support hardware, and an integrated system demonstration. Thruster, PPU, and flow system development is based on previous experience with SPT-100 system qualification and preliminary SPT-140 engineering model thruster development. The SPT-140 thruster effort, performed by EDB/Fakel and RIAME, begins with the design and testing of engineering model thrusters and concludes with the qualification of a flight-like thruster. In addition to the contractor's efforts, AFRL will perform life testing in support of the qualification effort. SS/Loral is developing the PPU for the system. The effort includes the design, fabrication, and test of breadboard through flight-like hardware. Flow system and other integration hardware will be used in conjunction with thruster and PPU hardware in the demonstration of system operation and performance. Program status is summarized below.

- Thruster Preliminary Design Review completed.
- Development and testing of engineering model thrusters completed. Thruster performance measurements confirmed that design would achieve the IHPRPT Phase I goal.
- Fabrication of optimized thruster (Demonstration Model) completed. The Demonstration Model thruster design and materials are consistent with a flight thruster, but fabrication is not required to include flight product assurance and configuration control requirements.
- Preparation of Thruster Qualification and Acceptance test plans initiated.
- Design of breadboard PPU completed. PPU performance models show that the design will achieve IHPRPT Phase I goals.
- Fabrication and test of breadboard PPU initiated.

### 5kW Univ. of Mich/AFRL Thruster

The University of Michigan and AFRL have jointly built a 5 kW class HET.[6] This thruster was developed to investigate, with a variety of diagnostics, a thruster similar to that specified by IHPRPT goals. The configuration of this thruster will be adjustable so diagnostic access to the interior of the thruster can be provided as necessary and to allow for the exploration of various thruster geometries. At nominal conditions, the thruster is designed to operate at 5 kW with a predicted specific impulse of 2200 s.

### 200W Hall Thruster Program

The AFRL has been funding THE Busek Co. for the past two years under a nearly completed Phase II SBIR program to develop a low power Hall thruster system including a miniaturized hollow cathode and low power PPU. The thruster intended for small, low power satellites is designed for nominal operation at 200 Watts. At this power it delivers about 10 mN of thrust at a specific impulse of about 1650 sec and peak discharge efficiency of 46%.

Scaling Hall thrusters downward toward minimum feasible size poses special design challenges including increasing magnetic field flux, increasing thermal loading and increasing particle impact/sputtering of

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the walls. Resolving these challenges led to a novel thruster geometry as depicted in Fig. 3.
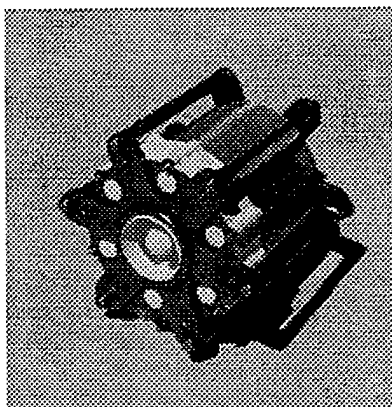


Fig. 3 BHT-200 Hall Thruster

All testing of this thruster, designated BHT-200, is carried out on a NASA style inverted pendulum thrust stand inside Busek's T6 facility capable of pumping 90,000 liters/sec of Xe. Depending on the pumping arrangement, the T6 tank pressure during the BHT-200 tests can vary from $10^{-7}$ to low $10^{-5}$ Torr.

A small 1/8" dia. hollow cathode is being developed concurrently with the 200W thruster to reduce the conventional ¼" dia. cathode propellant flow, heater and keeper power. This cathode, and similar designs, operated for several hundred hours with a typical mass flow of 0.05 mg/sec (about 10% of the 200W thruster flow) while delivering about 600 mA of current. The cathode will self sustain at this mass flow at about 900 mA. Higher mass flow, fewer watts of heater power, or smaller keeper current is required below 900 mA to sustain the cathode.

Concurrent with the thruster and the 1/8" cathode development, Busek designed and constructed a breadboard PPU/discharge power supply rated to deliver up to 400 Watts. The nominal input voltage is 28 VDC. Due to its advanced design, the PPU has real time adjustable voltage from 50V of 350 Volts, or real time adjustable current from 0 to 1.25 Amps - which is the short circuit protection limit. Resonant switching of the primary bridge allows the efficiency to be over 92% from 150 to 400 Watts with a peak efficiency of 94%. This efficiency includes the control/housekeeping power which is drawn from the 28 VDC source.

The first laboratory version of the BHT-200 thruster was delivered to AFRL. An improved model is scheduled to be delivered along with the 1/8" hollow cathode before the end of the fiscal year. The PPU breadboard delivery will follow. It is anticipated that

life testing of the system and transition to flight prototype development will occur during 1999.

## Racetrack Hall Thruster

The AFOSR is currently funding Busek under a Phase II SBIR contract to explore the potential of a large Hall thruster with racetrack shaped discharge cavity instead of the conventional circular cavity. Busek internally funded the initial feasibility experiments by building and testing a 200 W racetrack Hall thruster (designated BHT-RT-200. This was followed by a 2 kW thruster development, which is a linear scale up of the 200 W circular thruster, under AFOSR sponsorship in Phase I. The 2000 W thruster (BHT-RT-2000) is shown firing in Fig. 4. Based on the good results of those small thruster, 3 and 5 kW racetrack Hall thrusters are now under construction at Busek. At the conclusion of this program the 5kW racetrack thruster will be delivered to the AFRL for further testing.
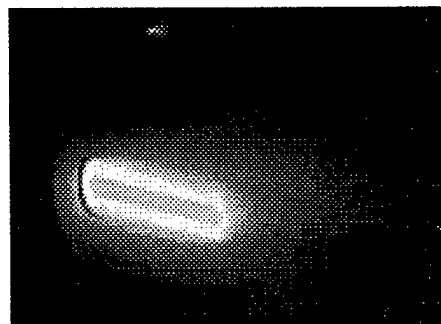


Figure 4. 2000W Racetrack Hall Thruster firing

The racetrack has several potential advantages relative to circular thrusters including:

- linear scale up utilizing demonstrated cross section (reduced development cost)
- potential for higher performance
- easier spacecraft integration including lower beam divergence
- significant thrust vectoring without gimbals

## T-40 Hall Thruster

A phase I SBIR has been funded to Space Power Inc. (SPI) to develop a unique Hall Effect thruster that operates over an input power range of 50 watts to 500 watts. The phase II should be awarded soon and result in a engineering model T-40 thruster. This thruster is expected to fill a unique role of primary propulsion for a significant number of small satellites and is applicable to East-West stationkeeping of large communication satellites. The design incorporates a new type of magnetic scheme that places the maximum magnetic field intensity outside of the channel's exit. This causes much of the ion acceleration to occur

outside the end of the thruster channel and should result in reduced erosion from ion sputtering. Two versions of the thruster are being fabricated. Advanced magnetic field modeling will be used to optimize the magnetic field, while finite-element modeling was employed for thermal and thermal stress/deformation analysis of the new thruster design. The thruster models will be tested for discharge stability, thrust performance, plume behavior, and a limited lifetime test of at least 100 hours.

## IV. Pulsed Plasma Thruster Programs

PPT has reemerged as an attractive propulsion option as greater emphasis has been place on reducing satellite size for many applications. PPTs are appropriate for low power levels (<100 W) and to provide exact impulse bits for use in accurate attitude control and constellation management. The main advantage of the PPT is the engineering simplicity which leads to high reliability. This reliability has been demonstrated by the successful application of PPTs in space missions starting in the late 1960s.

PPT research at the AFRL has focused primarily on propellant loss issues. Two major propellant loss mechanisms have been identified, late-time vaporization and particulate emission.[7,8] The late-time vaporization, observed using intensified broadband emission and heterodyne interferometry, is a continued boiling of the solid propellant surface for approximately 1 ms following the 20 µS discharge. Particulate emission was observed using broadband emission and surface analysis of witness plates in the exhaust. Large particulates of propellant material were found to be emitted from the thruster with a velocity near 200 m/s. Since there is no discharge current available to provide efficient electromagnetic acceleration for either the late-time neutrals or the particulates, they expand from the propellant face at low velocity creating negligible thrust. Between 80% to 90% of the propellant is estimated to be consumed by these two loss mechanisms severely limiting the overall efficiency attainable.

More recent work at AFRL initiated an investigation into the PPT energy loss mechanisms. A magnetic field probe diagnostic was developed and tested.[9] Measurements of the discharge arc and magnetic field structure with and without the probe immersed indicate that the probe is non-perturbing to the PPT plasma. Measurements of the PPT magnetic field structure show evidence for a propagating current sheet during the first half-cycle of the PPT discharge indicative of a Lorentz force acceleration. During the second half-cycle the magnetic field is observed to quickly diffuse

into the plasma. The energy dissipated in the second and subsequent current cycles primarily heats the plasma and represents a source of energy inefficiency in the thruster.

## V. Related EP Efforts

### Low Cost PPU Development

AFRL is managing a BMDO funded effort to demonstrate the feasibility of a compact, high power density, and low-cost PPU for a 100W class HET, with built-in expandability for a broad power range. SPI is being funded to develop a PPU that uses modular high power density DC-to-DC converters that feature redundancy, expandability, and will enable a short development cycle. SPI will develop a radiation hard, space qualified converter module based on a commercial version manufactured by Vicor. For phase I, SPI is designing, building, and qualifying a breadboard PPU which is anticipated to have a mass of less than 4 kg with 2N redundancy. SPI is also developing control circuitry that allows the output voltage to be adjustable over a range from 200 to 300V with a 28V input. This program is expected to validate a new approach to developing custom PPUs within a time period of 12-18 months.

### Field Emission Diamond Cathode

Busek is currently being funded under a Phase II SBIR Program to develop a diamond based field emission (FE) cathode for space propulsion applications. Motivation for field emission cathode stems from the deleterious impact of hollow cathodes on the performance (efficiency and Isp) of low power electrostatic thrusters including Hall and ion thrusters. The FE cathode is also ideal for neutralization of the colloid and FEEP thruster beams.

The deleterious impact of hollow cathodes is evident from the thruster efficiency equation:

$$\eta = \frac{T^2}{2(\dot{m}_a + \dot{m}_c)(P_{dis} + P_c)}$$

where T is thrust, $\dot{m}_a$ and $\dot{m}_c$ are the thruster anode and cathode flows receptively, and $P_{dis}$ and $P_c$ are the electric power dissipated by the discharge and the cathode including the keeper and heater power. Both keeper and heater may have to be activated while the small thruster discharge is on. From the above equation it is evident that when $\dot{m}_c$ approaches $\dot{m}_a$ as is the case for small (<200 W) Hall thrusters with conventional hollow cathodes, the system efficiency (η) can be reduced to a level that is unacceptable. By contrast, the FE cathode consumes no propellant and

only low power may be consumed by its gate (the equivalent of a keeper on the hollow cathode). The gate voltage and power is strongly dependent on the gate geometry and the properties of the emitter. Diamond, especially doped diamond with geometrical features that enhance local electric field (e.g. pyramid shape Spindt type cathodes) is an ideal material because it has electronegative properties and hardness needed to resist sputtering. Electronegativity in this case means that an electron is spontaneously ejected from the diamond into vacuum.

Busek measured emission from a flat diamond sample as high as 20 mA/cm$^2$. Typical emission curve vs. applied electric field is shown in Fig. 5. Currently, Busek is in the process of developing doped diamond deposition technology and surface morphology conducive to field emission. Testing is conducted in a small facility that has sealed (oil free), turbomolecular and cryogenic pumps to avoid contamination of the samples by hydrocarbons. At the conclusion of the program Busek anticipates delivery of a low power FE cathode prototype to AFRL.
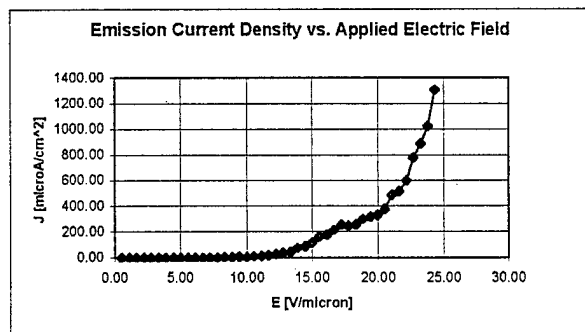


Fig. 5 Typical Diamond Emission

Free Molecule Micro-Resistojet

It is becoming evident that in many cases micropropulsion systems will not be simply scaled down versions of existing macroscale thrusters. As recently discussed by Muntz and Ketsdever[10] [ref. 1], the domain of small (in the limit micromechanical) propulsion systems offers many opportunities if the distinctive characteristics that dominate at small scales are exploited in an imaginative manner. One example of a unique microthruster, designed to show the utility of novel technology application, is the Free Molecule Micro-Resistojet (FMMR). The FMMR is characterized by unusually low stagnation pressures (50 to 500 Pa) and correspondingly large slot apertures. Free molecule flow is a limiting case where the molecular mean free path is large compared to a characteristic dimension of the flow. The free molecule condition requires that the expansion slot width-w be significantly less than a molecular mean free path in the stagnation chamber.

The FMMR offers several distinct advantages over conventional microthruster concepts for attitude control and station keeping maneuvers. The FMMR combines MEMS fabrication techniques with simple, lightweight construction consisting of only a polysilicon thin film heating element at a temperature Tw and a long exhaust slot. A long (~ 1 cm), narrow (1 to 100 μm) slot is an advantage over a small nozzle expansion because of the possibility for catastrophically plugging a nozzle throat (typically on the order of 20 μm in diameter) with contaminants. A slot is also significantly easier to manufacture. The free molecule condition is chosen for the additional benefit of reduced propellant storage pressure therefore easing propellant tank mass and valve leakage requirements. It appears that the most effective propellant for the FMMR is ice with the thruster operating on the vapor pressure.

For a thruster with a slot width of 100 μm and a length of 1 cm, the FMMR design produces a thrust of approximately 0.012 mN per slot with an Isp of approximately 68 sec. using an water vapor propellant as derived from the direct simulation Monte Carlo results[11]. Therefore, a thruster arrangement of 10 slots produces a total thrust of 0.12 mN at a heated wall temperature of 600 K. For applications which require large thrust levels, the stagnation pressure and wall temperature, and the total number of slots can all be increased to achieve the desired thrust level.

## VI. Basic Research Efforts

The Air Force Office of Scientific Research (AFOSR) is a major funding source in the nation for basic research in electric propulsion. They are presently funding 9 universities in the areas of: pulsed plasma thrusters, Hall effect thrusters, microwave thrusters and micropropulsion. An emphasis on low power has occurred within the last two years and corresponds with a national trend towards reducing the size of satellites. Summaries of many of the individual AFOSR electric propulsion programs can be found in reference.[12] Due to the companion paper, the University funded efforts will not be discussed in detail as has historically been done in previous years.

## VII. Conclusions

On-orbit electric propulsion offers substantial benefits to both the warfighter and the taxpayer. These benefits

can be realized once the risks associated with electric propulsion are both understood and minimized. Air Force missions that require electric propulsion include: precision stationkeeping for distributed satellite constellations, reposition assets, recover assets and re-deploy assets. The Air Force visionary report, New World Vistas strongly recommends the development of electric propulsion technologies.

The Electric Propulsion Space Experiment (ESEX) is the first high power (26kW) ammonia arcjet system to be tested and characterized in space. AFRL is coordinating a demonstration of a PPT on the MightySat II.1 space flight. The Air Force Office of Scientific Research (AFOSR) is a major funding source in the nation for basic research in electric propulsion devices: arcjets, Hall thrusters and pulsed plasma thrusters.

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